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ABSTRACT. The U.S. Navy Telesonar RDT&E effort is developing a low cost, non-coherent acoustic modem capable of data transmission under adverse channel conditions at data rates up to 2400 bits per second (bps). This modem was described at Oceans '97 in Halifax [1]. During the past year a substantial number of modems were constructed by Datasonics, Inc., including a some intended for deployment in the SEAWEB '98 series of acoustic experiments. These experiments will occur in September, 1998 in Buzzards Bay, Massachusetts, in the USA. The purpose is to demonstrate an acoustic network capability supporting approximately 10 modems deployed in very shallow water. The network consists of two groups of modems, each using frequency partitioning of the approximately 5 kHz of available bandwidth, to communicate independently with a master modem. The master modem then acoustically communicates with a gateway containing both cellular and RF communications capabilities to reach distant users. Communications amongst the modems involves message transfer ("hops") across several modems, thus requiring careful attention to the development and implementation of network protocols. This is the first in a planned series of network experiments involving increasingly sophisticated modems and protocols, with autonomous handshaking and adaptive modulation offering both much lower and much higher data rates than are now available.

I. INTRODUCTION

The US Navy is developing distributed underwater systems for various purposes, many of which require some form of wireless inter-sensor communications capability. The Office of Naval Research Deployable Autonomous Distributed System (DADS), in particular is developing a system of distributed sensor nodes of several types which must provide contact, environmental, local system status, and timing data to a central node for data fusion and communication with the outside world. During the early phases of this project, both acoustic and non-acoustic methods of communications among the sensor nodes were considered, but the difficulties and uncertainties of the non-acoustic techniques were quickly realized. The Telesonar project was authorized to begin conceptual development of an acoustic modem to provide reliable connectivity amongst the nodes of the DADS network.

The development of a network-capable modem was enhanced by an existing Navy SBIR with Datasonics, Inc., supported by Delphi Communication Systems, Inc. to develop a second generation acoustic modem to extend the capabilities of the Datasonics ATM 850 modem [2]. This work resulted in the new Datasonics ATM87x series modems. The ATM87x provides the user with an expanded selection of modulation and coding formats, lower power consumption, lower cost and other features.

An option in the SBIR contract provided funding to modify the ATM87x to operate in a network environment that meets the needs of the Telesonar project. SEAWEB '98 will be the first in a series of yearly experiments where the ATM87x and other networked Telesonar modems will be demonstrated with the ultimate goal of proving advanced capabilities that are suitable for DADS use.

II. THE NEW ATM87X MODEM

The ATM87x is similar to the previous ATM-850 product in that it uses robust Multiple Frequency Shift Keying (MFSK) modulation. However, the ATM87x was designed to cost less and use less power. By reducing the analog electronics and requiring the DSP to perform more processing, a 75% reduction in PC board space was achieved.

The ATM87x uses 120 frequency bins in 4800 Hz allowing up to 60 bits to be transmitted in a 25-ms symbol frame. This results in a maximum bit rate of 2400 bps. In addition, flexibility is provided in software to increase frequency diversity by mapping a given set of two data bits to one or more groups of four tones. In the most redundant case, two bits could be mapped to all 30 groups of four tones, providing significant anti-fading/anti-noise capability at the expense of a lower 80-bit/s throughput.

A more efficient approach to combat fading is provided by Hadamard MFSK. This mode relies on the use of codewords derived from the family of (20,5) Hadamard codes. These 20-bit codewords each have 10 ones and 10 zeros. 32 different codewords are used where each is mapped to a unique pattern of 5 input bits. Every sixth tone of the 120 total tones is mapped to a bit of a codeword. Ones in each codeword indicate active tones and zeros indicate inactive tones. Up to 6 codewords or 30 bits can be encoded simultaneously in the available 120 tones. By choosing every sixth tone, each codeword is spread over 4800 Hz of bandwidth. The coding gain provided by the Hadamard codes allows one or two tones to fade without significant impact on

the received BER. As in the 1-of-4 MFSK case, the same set of 5 bits can be encoded in 2, 3, or 6 codewords to further increase frequency diversity at the expense of data rate. LPD/LPI applications with low data rate requirements are likely to use multiple Hadamard codewords to send the same 5 bits so that sufficient energy per bit is obtained while minimizing the levels of the discrete tones. Hadamard codes increase the effective receiver SNR by providing additional coding gain. Hence Hadamard codes are a more efficient use of the available spectrum than arbitrary mapping of bits to more and more 1-of-4 MFSK tone groups. Figure 1 shows the improvement in modem BER performance using Hadamard (20,5) MFSK relative to 1-of-4 MFSK with frequency diversity 2 (D2). The simulated results were obtained using the Rayleigh channel model representing more pessimistic propagation conditions than would typically be encountered. In the simulation, the Hadamard scheme uses 20 tones (10 active) to send 5 bits, while the 1-of-4 MFSK D2 scheme uses 8 tones (2 active) to send 2 bits. Both methods have a bandwidth expansion factor of 4, i.e., both require 4 tones of bandwidth for each bit sent. Clearly the Hadamard scheme provides a significant decrease in BER for increasing levels of SNR per bit. At low SNR per bit the curves cross which might prompt one to select 1-of-4 MFSK for LPD/LPI applications. However, note that the Hadamard scheme uses 2 active tones per bit while the 1-of-4 scheme uses 1 active tone per bit. Thus a modem using the Hadamard (20,5) MFSK scheme can transmit tones 3dB lower than a comparable 1-of-4 MFSK D2 scheme.

ISI is reduced by providing a mechanism to avoid symbol overlap due to multipath delay. The new modem design implements this feature by prepending a portion of a given data symbol to its beginning at the transmitter. The length of the prepended signal (multipath guard period) is

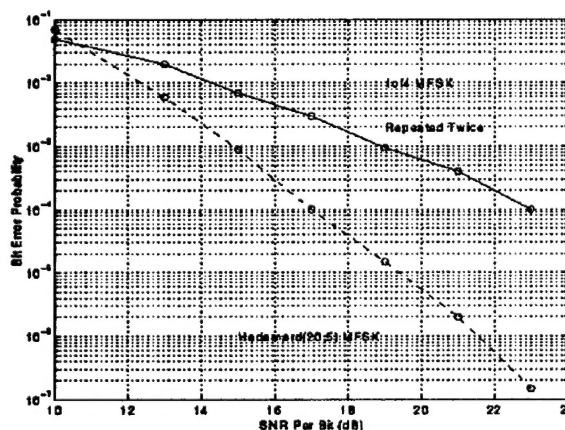


Figure 1. BER performance of Hadamard (20,5) MFSK and 1-of-4 MFSK with diversity 2 (D2) selectable and is optimally set to the length of time significant multipath persists in the communication channel. Clearly this

reduces the data transmission rate; however, the receiver will be able to track symbol periods within which there is no ISI. Since the transmitter and receiver are FFT-based, the signal phase for a given transmitted tone is guaranteed to be continuous across the boundary between the symbol and the prepended portion even if the prepended portion is longer than the symbol itself. This implies that the symbol period of acoustic signal processed at the receiver will be free of discontinuities from adjacent symbols or from own-symbol multipath interference. Therefore the common effect known as DFT "leakage" will be avoided in the receiver FFT result and the level of self-noise or interference is greatly reduced.

Another new feature added to the MFSK modem is the ability to translate the 5-kHz band anywhere within the 1-35 kHz spectrum. This allows the modem to be tailored to different applications with diverse interference characteristics and ranges. This is accomplished in software using a quadrature mixer that converts between passband and baseband and interpolation (decimation) stages in the transmitter (receiver). A time- and frequency-scaling feature has also been added so that applications below 10 kHz with limited transducer bandwidth can use $\frac{1}{2}$, $\frac{1}{4}$, or $\frac{1}{8}$ of the 5120 Hz band while increasing the symbol period of 25ms by 2, 4, or 8.

Acoustic doppler detection and correction capability has also been incorporated into the ATM87x. This feature will permit the ATM87x to communicate with moving ships and remote vehicles. A test program to determine the performance envelope of this feature is currently underway at Datasonics.

III. AT-SEA TESTING AND USE

The ATM87x series of modems have experienced a substantial number of tests and applications including:

- U.S. Navy testing in San Diego: Shallow water testing of the various modulation modes and bit rates was accomplished in very shallow water in San Diego harbor, and were then repeated in 200 meter water depths several miles offshore. Using omnidirectional transducers, ranges exceeding 5 Km were achieved. A pitch, roll, and heading sensor was connected by external RS-232 serial cable. The sensor package was then controlled acoustically, with data acquired at a commandable repetition rate. A test message was also transmitted periodically to determine error rate, SNR, and multipath time.
- NOAA sponsored deep water vertical channel testing: NOAA is installing a series of deep ocean moorings in the Northern Pacific for the purpose of detecting tsunami events. Each surface buoy contains a Telesonar acoustic modem interfaced with a GOES satellite transmitter. Hourly communication between a bottom acoustic modem / pressure sensor provides continuous monitoring of sea surface level. If a tsunami related pressure increase is detected, the system is programmed to provide an immediate warning.
- Monitoring of a cable trenching plow under tow in water depths up to 1000 meters. A pitch, roll and heading sensor has been integrated with an acoustic altimeter to provide

data for transmission by acoustic modem from the seafloor towed trenching plow to a ship deployed transducer. The plow is towed at slow speed and must maintain a stable attitude during the survey operation.

- Offshore pipelay monitoring: Petrobras is using acoustic modems to monitor stresses in a J-lay operation where pipe is laid on the seafloor and then "bends" upward to terminate at a floating, anchored, semi-submersible production platform in 1000 meters of water. Stress sensors are located at several positions along the section of pipe where the maximum bending and touchdown with the seafloor is taking place. Control and monitoring are implemented with bidirectional acoustic modems.

IV. NETWORKING AND SEAWEB '98

The practical development of undersea sensor systems like DADS requires highly capable communications among the nodes of the system and with the end-user of the system. Advancements in both underwater and wireless RF communications provide a unique opportunity to combine technologies to transport data from underwater sensor systems back to sea and land based assets for further processing. To be useful to the Navy, the communication system must use robust protocols, operate semi-autonomously, and have a measure of covertness. To this end, the Telesonar project will combine enabling technologies with the ultimate goal of providing an acoustic network that meets DADS needs.

The SEAWEB '98 experiment is the first in an anticipated series of yearly experiments designed to advance the state of the art in undersea wireless communications. The principal goal of this initial 2-week trial is to demonstrate the use of the ATM87x modem in a network environment and to demonstrate various 2-way gateways to terrestrial users. This test will employ both cellular telephones and Freewave RF links for the latter purpose.

Although the ATM87x was not designed for asynchronous multi-user access, the existing modem software will be modified to incorporate a form of Frequency Division Multiple Access (FDMA) in controlled situations for experimenting with protocol concepts, link-layer requirements, etc. In the near future an advanced modem, now under development by Datasonics and Delphi Communication Systems, will incorporate the Type B signaling method as the backbone method for acoustic networks¹.

The ATM 875 signaling formats have been modified for the SEAWEB experiments to support simultaneous, half-duplex multi-user connectivity by allocation of specified portions of the available bandwidth to specific clusters of modems. This modified frequency reuse allocation supports a network of about 10 subsurface modems in two clusters, as shown in Figure 2. Cluster A contains 3 modems, cluster B contains 4 modems, and there is one Master Node (M) and one

Gateway Node (G). The Master Node serves as a central access point for the entire network and the Gateway Node is dedicated to the acoustic-to-RF interface. There is also one independent modem contained within the Telesonar Testbed ("G") [5] for monitoring purposes.

SEAWEB '98 will be deployed in Buzzards Bay in Massachusetts. The region has a water depth of approximately 30 feet with a sandy bottom. There is expected to be a 22 Deg C water temperature down to a depth of 9 feet where an abrupt thermocline from 22 to 15 Deg C is expected. Network nodes will be deployed initially with a 1-2 nautical mile separation. The Gateway node is positioned within acceptable range of a nearby cellular phone tower. If conditions permit, the separation may be increased.

The network spans a shipping lane that extends from the nearby Cape Cod Canal. There are expected to be periods during which acoustic noise is high due to passing ships and power boats. Additionally, a current up to 1 knot is possible during tide changes. The shallow water and other conditions provide a complex acoustic environment in which to test the robustness of SEAWEB. The close proximity to shore and Datasonics facilities permit regular access to network components.

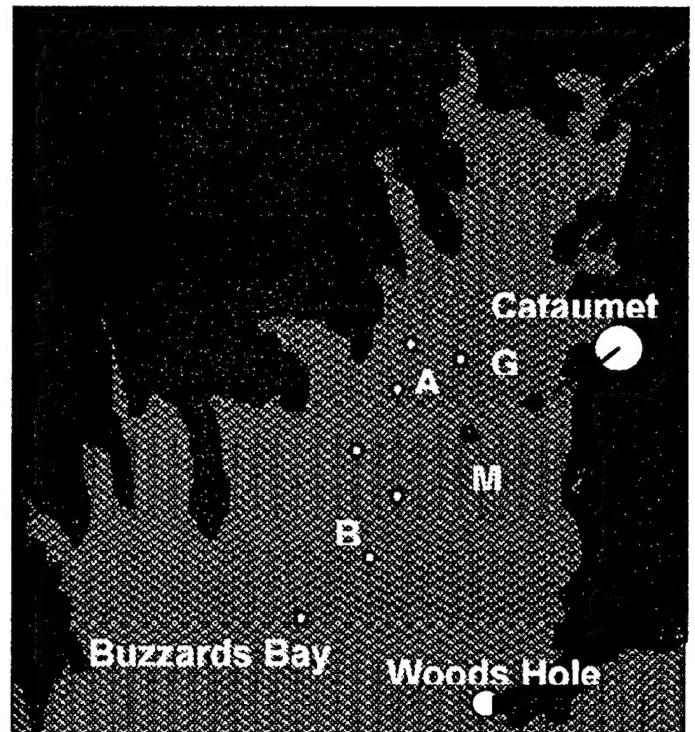


Figure 2. Topography of SEAWEB '98

¹ See the contributed paper by Green and Rice, "Handshake Protocols and Adaptive Modulation for Underwater Communications Networks," in the Oceans '98 Conference proceedings.

IV.1 A Layered Protocol

The multi-node SEAWEB '98 protocol contains three layers that expand existing point-to-point protocol used in the ATM87x series modems.

Layer 1 describes the acoustic signaling used between a pair of communicating modems. The ATM87x modulation formats described in section II provide data rates from 100 to 2400 bps using 4800 Hz of acoustic bandwidth. This use of the available frequency band precludes multiple simultaneous modem communications due to frequency overlap.

To support the multi-node requirements of SEAWEB, the standard ATM87x modulation scheme will be modified to utilize a FDMA scheme. Each network cluster is assigned a unique set of twenty tones to which Hadamard (20,5) modulation is mapped. In addition, communication between the two clusters and the Master Node and the Gateway Node and the Master Node use a third unique set of tones. When combined with Rate 1/2 convolutional error correction coding and a multipath guard period, the effective bit rate becomes 50 bps per cluster. To further minimize crosstalk, unused guard frequencies are allocated between adjacent tones. Layer 1 also provides for unique acoustic ids that permit modems to remain in a low power state (2.5 mW) until addressed by another modem.

Layer 2 will be a modified version of the ATM87x protocol for modem-to-modem communication. This layer describes the format of control information encoded in an acoustic packet. The ATM87x uses the concept of a COMMAND or DATA packet. COMMAND packets are typically used to modify parameters in a remote modem, or to command the remote modem to change to a different operating state. DATA packets contain strings of user information. SEAWEB Layer 2 uses both COMMAND and DATA formats to ensure that Layer 3 information is communicated properly between a pair of modems. Two modes of transport are available at Layer 2. The *Errorable* mode allows Layer 3 information to be passed between modems with bit errors. This is useful when instrument data is being sent back to the central node where a few bit errors may be filtered out. The *Errorfree* mode requires Layer 2 to retry transmissions of acoustic packets several times in an attempt to transport the Layer 3 information without errors. This mode is necessary when commands are transported between modems and no errors may be tolerated.

Layer 3 provides mechanisms to perform the multi-node SEAWEB protocol described in section IV.2. Whereas Layers 1 and 2 are modified versions of existing capabilities, Layer 3 is a new enhancement to the ATM87x. At this layer, additional routing information is added so that a packet of data can traverse the network from one modem to another. This includes a source id, a destination id, and additional checksums. Layer 3 utilizes the services of Layers 2 and 1 to transport its packets between a given pair of modems.

IV.2 Protocol Operation

The SEAWEB '98 protocol is a first step toward the application of more extensive routing capabilities that will be included in future SEAWEB experiments. In SEAWEB '98 the network is initialized with routing information prior to deployment and does not require automatic reconfiguring. Ultimately DADS applications will require such capabilities.

The protocol views each network cluster as a branch of a binary tree. A modem is considered a *node* in the tree branch with the most distant modems from the Master Node assigned to the *leaf* nodes. The Master Node is the *root* of the tree, so all traffic between the Gateway Node and a cluster occurs via the Master Node. Traffic between clusters is also passed through the Master Node.

Each branch node maintains a list of neighbor node ids formatted as a binary tree branch. The set of node ids between a given node and the leaf nodes, and one node closer to the Master Node is sufficient routing information to send a packet anywhere in the network. Figure 3 shows an arbitrary tree branch that could be maintained by Node Id 3. Note that the assignment of node ids are not ordered in any way. The assignment of nodes to the binary tree is determined by the location each node is given in the network at deployment time. The protocol begins when one of the following information sequences is obtained by Layer 3:

- Data generated by a device attached to the node.
- Internally generated test data
- An information sequence received from another node on route to a recipient node.

The protocol proceeds as follows:

- If the recipient node given by byte 1 is in the binary tree at a higher level, then Layer 3 informs Layer 2 that the information sequence should be passed to the neighbor node that has an id in the same subtree as the recipient node. For example, in Figure 2, if the recipient node id was 5, the destination id for Layer 2 would be 99 instead of 150 since node id 5 is in the subtree through node 99.
- If the final destination node is not at a higher level in the tree, Then Layer 2 will be informed to pass the information sequence to the node one level lower than the current node. In Figure 3, this would be node id 6. The information sequence will ultimately reach its recipient node by traversing the network binary tree.

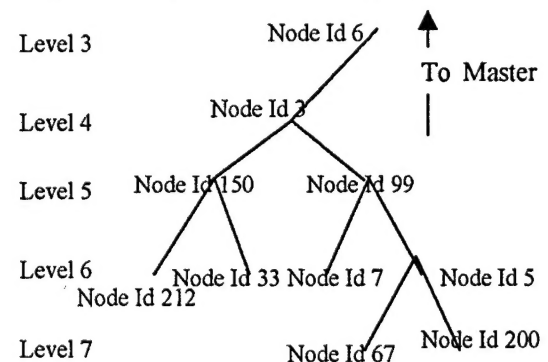


Figure 3. Binary Tree for Node Id 3

IV.3 RF Links

Two RF links will be used to demonstrate the air interface requirements of a DADS network application. Ultimately satellite and Navy radio links will be used for this purpose. For SEAWEB '98, A cellular telephone link and a Freewave packet radio will be used to provide a link to the Gateway node. These links will be transparent to operators on the shore who will issue commands and receive data directly through the RF link to an acoustic modem in the Gateway. The Gateway node will use a surface buoy to house electronics and batteries

V. FUTURE DEVELOPMENTS

Datasonics and Delphi are developing a new modem, based in part on the current ATM 875. It is being designed to provide both very low data rate communications based on the Telesonar type B signaling (frequency hopped, M-ary FSK, or FH/MFSK) [reference], and very high data rates based on adaptive channel equalization. It will also provide the intermediate signaling schemes currently available in the ATM 875, and a direct sequence, DS/CDMA with RAKE scheme developed by Delphi. The FH/MFSK will provide handshaking protocols and channel characterization for adaptive modulation, while it and the DS/CDMA technique will provide excellent multi-user access to the channel. It is anticipated that this modem will be used in the Sea Web '99 experiments, to be described at a later time.

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